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Much of our observational effort over the three year period of this grant has focused on collecting, reducing and interpreting our observational data taken at Sacramento Peak Observatory in New Mexico. From this effort and our theoretical work, we have demonstrated that there are two co-existing five minute period period phenomena on the Sun's surface. The first is the well-known oscillations we study to determine internal properties of the Sun. Best known among these properties is the Sun's internal rotation rate. The second one is the residual of the excitation acoustic events. The acoustic events are the smoke from the fire exciting the solar oscillations.

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FINAL REPORT ON AFOSR-92-0094

Philip Goode, PI

This is the final report on AFOSR-92-0094 covering the period 11/1/91-10/31/94. This report also covers the period of 11/1/94-3/31/95 for which the grant was extended to enable Dr. Thomas Rimmele to finish his work. During this whole period, we have applied for no patents.

Dr. Thomas Rimmele has finished his postdoctoral appointment, and has accepted a tenure track appointment at the National Solar Observatory in Sunspot, New Mexico. In his new position, he will continue his observational work with us. His collaboration will be especially important in our efforts to perform observations in the infrared under AFOSR-95-0070. These observations will be led by our new postdoctoral associate, Dr. Louis Strous. Dr. Strous is supported on the renewal of the grant which is the subject of this report. In the first year of AFOSR-92-0094, Dr. Sergio Restaino was the postdoctoral associate. Dr. Restaino is now an Air Force Senior Research Associate at Kirtland Air Force Base in New Mexico. He is working on the adaptive optics effort at Kirtland.

A list of the publications under AFOSR-92-0094 is appended to this report.

The theoretical basis for much of our observational work was done under this grant in collaboration with Gough and Kosovichev. Several years ago, Stebbins and I observed that there is a five minute period acoustic phenomenon which exhibits large positive and negative phase changes through the photosphere. Such changes would be inconsistent with the properties of the well-known five minute period global oscillations which should be evanescent in the photosphere. It is from this that Gough, Kosovichev and I showed that, in principle, there are two distinct five minute period acoustic phenomena in the photosphere. The first is the global five minute oscillation from which all of the impressive helioseismic results have followed. The second is impulsive acoustic events excited by convection. We showed that the acoustic events act as an acoustic probe. We showed that the probe originates just beneath the photosphere by about 100km. The probe is created in

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individual events of excitation of solar oscillations. To verify this picture, Stebbins, Restaino and I looked for the individual acoustic events as described in our theoretical picture. In the picture, individual acoustic events first have a maximum in the upgoing flux and then the velocity amplitude reaches a maximum and then the downgoing flux is maximal. In our analysis of our observational data, Restaino, Stebbins and I looked for the correlation between the flux and the velocity amplitude through all the data; we found the temporal ordering predicted by the model. That is, the maximum of the upgoing flux precedes the maximum in the velocity amplitude by about a minute, and the maximum in the upgoing flux precedes that in the downgoing flux by about six minutes. We have also made movies of the data and there are many individual events in which the behavior can be seen.

Much of our observational effort over the three year period of this grant has focused on collecting, reducing and interpreting our observational data taken at Sacramento Peak Observatory in New Mexico. From this effort and our theoretical work, we have demonstrated that there are two co-existing five minute period phenomena on the Sun's surface. The first is the well-known oscillations we study to determine internal properties of the Sun. Best known among these properties is the Sun's internal rotation rate. The second one is the residual of the excitation of that oscillation. We call these latter phenomena acoustic events. The acoustic events are the "smoke" from the "fire" exciting the solar oscillations.

Rimmele, Stebbins and I have extended our earlier observations into three dimensions covering a sizable two-dimensional patch of the Sun's surface. From our recent observations we have learned, for the first time, the surprising source of solar oscillations. We simultaneously observed the granulation with one CCD and with a second the Doppler shift in the 543.4nm FeI line using the Fabry-Perot device on the Vacuum Tower Telescope of the National Solar Observatory so that we could make full three dimensional observations of the Sun's vertical and horizontal velocity fields. Our field of view is about 100"x100" and the line is digitized at 16 points. We have a 0.3" pixel spacing in the field of view and we determine vertical velocities from the Doppler shifts as a function of depth in the Fe line. With these, we have sufficient information to separate the

global oscillations from the acoustic events. From the acoustic events, we calculate the localized mechanical flux from the excitation of the oscillations. We then superimpose the acoustic events on the granulation.

We find that the acoustic events occur preferentially in the dark lanes in the granulation. In fact, they occur in dark lanes when the lanes suddenly and abruptly get much darker. This means that solar oscillations are not excited by the continuous convective drumming of the upwelling convection, as most people believed. Rather, they are excited by the local catastrophic cooling and subsequent collapse of the solar surface. The dominance of the surface region means that the Sun's convection can be regarded as a surface driven opacity phenomenon. This work is described in our paper which will appear in Astrophysical Journal Letters later this year. This work is important in efforts to understand the nature of the Sun's convection which is critical in any effort to understand activity. In fact, under the currently active grant, we will be collaborating with Dr. Mark Rast of the High Altitude Observatory concerning the implications of these observations. Major progress has been in our understanding of convection by exploiting large-scale computer simulations of convection. However, these calculations have not yet been properly compared with observations. In particular, our observations in the infrared that will be done in the future will provide guidance by fixing the outer boundary conditions for the simulations. This will allow the first self-consistent simulations. The point of the upcoming observations is that in the infrared there are lines formed beneath the photosphere, and we will then probe the outer boundary region used in the simulations.

The Sun's activity cycle is due to the combined actions of rotation, magnetism and convection. In a major part of the theoretical work under AFOSR-92-0094 grant, we have focused on the nature of rotation and magnetism near the base of the Sun's convection zone. This focus is motivated by work from our previous AFOSR grant in which Dziembowski, Libbrecht and I showed that the base of the convection zone is the site of the creation of the toroidal magnetic field which subsequently emerges through the solar surface as the many forms of activity. In detail, the  $\alpha$  and  $\Omega$  dynamo

actions needed to generate the toroidal field require the confluence of sizable radial and latitudinal gradients in rotation--we used oscillation splitting data to reveal that this confluence occurs only near the base of the convection zone.

In the theoretical work on AFOSR-92-0094, I have shown that the change in the sun's internal rotation over the sun's activity cycle occurs just above the base of the convection zone. This lends strong support to theories of the solar dynamo in which the dynamo is situated at the base of the convection zone. Further, Dziembowski and I have developed a seismic method to directly determine the Sun's internal angular momentum from seismic data. Understanding the spin-down of the Sun's angular momentum is critical in any effort to advance stellar evolution theory.

In addition, we have inverted the symmetric part of the Big Bear Observatory oscillation data. From this seismology, we have learned that there is some permanent distortion of the Sun acting near the base of the convection zone. This is probably related to the solar activity dynamo in some, as yet unknown, way.

In all of the inversions for internal rotation, it has been implicitly assumed that the Sun rotates on a single axis. Mike Thompson and I have seismically demonstrated this using Big Bear data. We used BBSO data to show that the outer half of the Sun by radius rotates on a single axis to better than a 0.1 rad. We also solved a similar problem in unsteady perturbation theory to place limits on inclined magnetic fields. We showed that like the case of an inclined rotating region, an inclined magnetic field would induce a hyperfine splitting in the spectrum of solar oscillations which would be manifest in linewidth data. Using the Big Bear linewidth data, we find that a sizable inclined field could only be hidden deep in the radiative interior where it could evade the seismic detecting powers of available data.

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